Exhibit A

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Encyclopedia of Laser Ph

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Last update: 2008-07-15

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Relative Intensity Noise

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Acronym: RIN

Definition: noise of the optical intensity (or actually power), normalized to its average value

In the context of intensity noise (optical power fluctuations) of a laser, it is common to specify the *relative intensity noise* (RIN), which is the power noise normalized to the average power level. The optical power of the laser can be considered to be

$$P(t) = \bar{P} + \delta P(t)$$

with an average value and a fluctuating quantity δP with zero mean value. The relative intensity noise is then that of δP divided by the average power; in the following, this quantity is called I. The relative intensity noise can then be statistically described with a power spectral density (PSD):

$$S_I(f) = \frac{2}{\bar{P}^2} \int_{-\infty}^{+\infty} \langle \delta P(t)\, \delta P(t+\tau) \rangle \exp(i 2\pi f \tau)\, \mathrm{d}\tau$$

which depends on the noise frequency f. It can be calculated as the Fourier transform of the autocorrelation function of the normalized power fluctuations (see the equation), or measured e.g. with a photodiode and an electronic spectrum analyzer. (The factor of 2 in the formula above leads to a one-sided PSD as usually used in the engineering disciplines.) The units of this RIN PSD are Hz^{-1}, but it is common to specify 10 times the logarithm (to base 10) of that quantity in dBc/Hz (see also: decibel). The PSD may also be integrated over an interval $[f_1, f_2]$ of noise frequencies to obtain a root mean square (r.m.s.) value of relative intensity noise

$$\left.\frac{\delta P}{\bar{P}}\right|_{\mathrm{rms}} = \sqrt{\int_{f_1}^{f_2} S_I(f)\, \mathrm{d}f}$$

which is then often specified in percent.

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Note that it is not sensible (although common) to specify relative intensity noise in percent (e.g. as ±0.5%) without clarifying whether this means an r.m.s. value or something else. See the article on noise specifications for more such details.

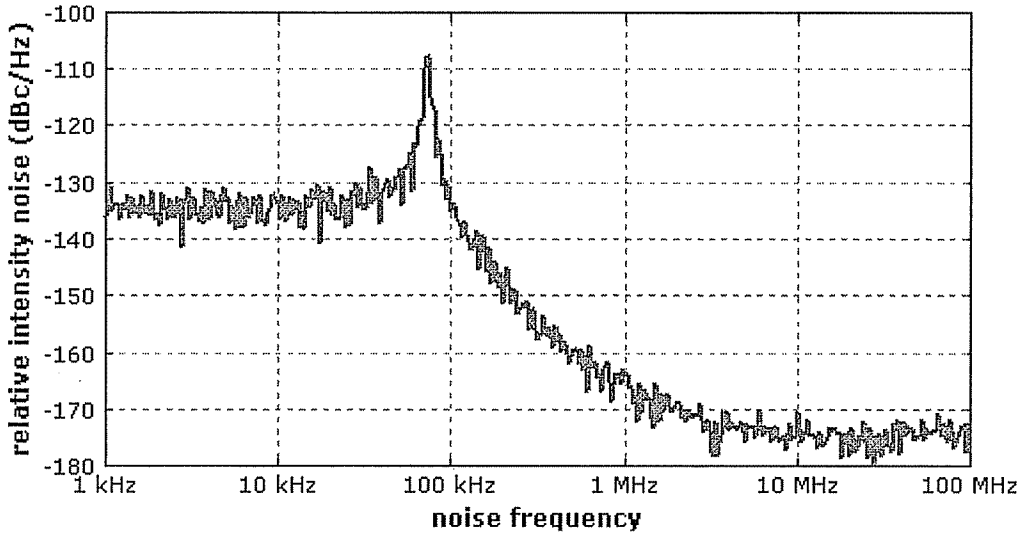


Figure 1: Simulated relative intensity noise spectrum of a 1064-nm Nd:YAG laser with 100 mW average output power. The shot noise level of −174 dBc/Hz is reached above 5 MHz. There is also a pronounced peak from relaxation oscillations, and excess noise at low frequencies introduced by the pump source.

RIN from Shot Noise

It might be expected that the amount of RIN of a laser beam will remain constant when the beam is subject to linear attenuation. This is not true, however, when the RIN is limited by shot noise. In that case, the RIN is given by

$$S_{I,\mathrm{sn}}(f) = \frac{2h\nu}{\bar{P}}$$

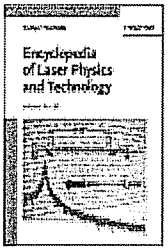
As an example, a 1-mW laser beam at 1064 nm with intensity noise at the shot noise limit has a RIN of $3.73 \times 10^{-16}\,\mathrm{Hz}^{-1}$ or −154 dBc/Hz.

This PSD is independent of noise frequency (*white noise*), and it increases with decreasing average power. This can be understood as the introduction of additional quantum noise in the attenuation process.

Quantum-limited RIN measurements should be done by detecting the entire laser power e.g. with a photodiode, while minimizing the influence of excess noise (e.g. thermal noise) from the electronics.

See also: intensity noise, noise specifications, quantum noise

Categories: fluctuations and noise, lasers



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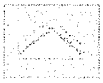
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